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Idealized Modeling Studies of Long-Lived Large Amplitude Inertia Gravity Waves

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6. AUTHOR(S)
Lance F. Bosart
Daniel Keyser

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Ms. Margaret O'Brien
Research Foundation of SUNY
1400 Washington Avenue
Albany, New York 12222

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Major Paul Bellaire
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13. ABSTRACT *(Maximum 200 words)*

AFOSR/ASSERT funds for FY-99 have been used in support of: (1) continuing research designed to elicit the three-dimensional structure and evolution of large-scale environments conducive to the formation and presence of long-lived large-amplitude inertia-gravity waves (IGW); (2) IGW case studies IGWs in support of (1); and (3) the preparation and submission of manuscripts describing previously completed research findings for formal publication (abstracts are attached elsewhere to this report).

The results from (2) show that a significant mesoscale pressure disturbance passes through the Flatland Atmospheric Observatory just after 1600 UTC 28 April 1996. This originated over northeastern KS and is associated with the back edge of a stratiform rain region which extends north of mesoscale convective system. NCEP Reanalyses and NWS soundings show that this convective event occurs in a region with many characteristics of an inetia-gravity wave environment (see report for FYs 97 and 98). The 50 MHz profiler shows that the wave is associated with strong downward motion in the middle troposphere. It is hypothesized that this downward motion penetrates into the low-level stable layer creating substantial adiabatic warming and hence driving the pressure falls observed at the surface.

14. SUBJECT TERMS
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Structure of large-amplitude propagating gravity waves.

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Idealized Modeling Studies of Long-Lived Large Amplitude Inertia Gravity Waves

Co-Principal Investigators:

Lance F. Bosart
Department of Earth and Atmospheric Sciences, ES-227
State University of New York at Albany
1400 Washington Avenue
Albany, New York 12222

Phone: 518-442-4564 FAX: 518-442-4494
EMAIL: bosart@atmos.albany.edu

Daniel Keyser
Department of Earth and Atmospheric Sciences, ES-224
State University of New York at Albany
1400 Washington Avenue
Albany, New York 12222

Phone: 518-442-4559 FAX: 518-442-4494
EMAIL: keyser@atmos.albany.edu

1 December 1999

I. SUMMARY OF RESEARCH PROGRESS

1. Completed Work:
   a) A manuscript by Bosart, Bracken, and Seimon describing the results of an analysis of the long-lived large-amplitude inertia-gravity wave (IGW) event of 4 January 1994 over the northeastern United States has been published by the *Monthly Weather Review*. A copy of the abstract of the paper is attached.
   b) A manuscript by Koppel, Bosart and Keyser describing the results of a climatology of large-amplitude IGWs over the continental United States will appear in the January 2000 issue of the *Monthly Weather Review*. A copy of the abstract of the paper is attached.
   c) Eric Hoffman completed and presented the results of a composite analysis of the three-dimensional structure and evolution of large-amplitude inertia-gravity wave environments at the American Meteorological Society's 17th Conference on *Weather Analysis and Forecasting*, 13-17 September 1999 in Denver, Colorado. A copy of the preprint from the latter is attached. A manuscript by Hoffman, Bosart, and Keyser detailing these results is under preparation and will be submitted for formal publication during the spring of 2000.
   d) Preliminary diagnosis of a mesoscale pressure disturbance in the midwestern United States on 28 April 1996 was completed and presented at the American Meteorological Society's 8th Conference on Mesoscale Processes 28 June - 1 July 1999 in Boulder, Colorado. A copy of the preprint from the latter is attached.

2. Ongoing Work:
   a) Eric Hoffman is completing research involving case studies of the gravity wave and wake low wave events of April 1996 in order to investigate the mesoscale structure and evolution of this case. Data sets and wavelet analysis techniques provided by Dr. Einaudi of the National Aeronautics and Space Administration's (NASA) Goddard Space Flight Center, WSR-88D radar data from the National Weather Service, and 404 MHz NOAA profiler data provided by Paul Neiman form the basis of this investigation.

Ongoing research on Task I.2a shows that a single wave of depression moves through the Flatland Atmospheric Observatory (FAO) Microbarograph network just after 16 UTC 28 April 1996 (Fig 1a.) with pressure falls of ~8 hPa in 30 minutes (Fig. 1a). The meteorological observations from Flatland show that the wave is accompanied by gusty easterly winds (Figs 1b and 1c). Wavelet analysis of the FAO network is used to identify the following wave characteristics: 1) a peak-to-peak amplitude of 6.04 hPa, 2) a period of 4.4 h, and 3) a phase speed of ~21 m s^{-1} toward the east-southeast. Vertical velocities from a 50 MHz profiler show that the pressure falls are associated with a distinct maximum in downward vertical velocity in the middle troposphere (Fig 2). Analysis of the NWS WSR-88D data suggest that this wave occurs on the northwestern edge of a stratiform rain region associated with a mesoscale convective system across southern Illinois. Analysis of the radar and profiler data as well as conventional surface observations reveals that this wave of depression originate in northeastern KS at about 0900 UTC and moves east with MCS across north central Missouri, central Illinois before dissipating in central IN at about 20 UTC 28 April 1998.

II. CURRENT PROJECT STATUS:

Current work is focused on Eric Hoffman's doctoral dissertation research. Grant funds have been exhausted. We are, however, in the process of completing the publication of results supported by former AFOSR Grant # F49620-95-1-0492DEF.

III. PUBLICATIONS:

1. Refereed:

Bosart, L. F., W. E. Bracken, and A. Seimon 1998: A study of cyclone mesoscale structure with emphasis on a large-amplitude inertia-gravity wave. *Mon. Wea. Rev.*, **126**, 1497-1527.

Koppel, L. L., L. F. Bosart, and D. Keyser, 2000: A 25 year climatology of large-amplitude inertia-gravity waves over the conterminous United States. *Mon. Wea. Rev.* **127**, 51-68.

2. Preprints:

Hoffman, E. G., L. F. Bosart, and D. Keyser, 1999: Mesoscale structure and evolution of large-amplitude inertia-gravity waves.: A Case Study. Preprint volume, Eighth Conference on Mesoscale Processes, American Meteorological Society, 28 June - 1 July 1999, Boulder, Colorado, pp 101-102.

Hoffman, E. G., L. F. Bosart, and D. Keyser 1999: Large-amplitude inertia-gravity wave environments: Large-scale structure and evolution. Preprints, 17th Conference on Weather Analysis and Forecasting, American Meteorological Society, 13-17 September 1999, Denver, Co, 38-39.

3. In preparation:

Hoffman, E. G., L. F. Bosart, and D. Keyser, 2000: Large-amplitude inertia-gravity wave environments: Three dimensional structure and multiscale evolution. In preparation for submission to *Mon. Wea. Rev.*

IV. PROJECT PERSONNEL:

Co-PIs:	Lance F. Bosart
	Daniel Keyser
Staff Support:	Anton Seimon
Graduate Students:	Lorna Koppel (September 1993 - December 1995)
	W. Edward Bracken (beginning October 1993)
Administrative Support:	Celeste Iovinella

V. BUDGET:

Funds exhausted as of 8/31/99.

VI. TECHNOLOGY TRANSITIONS:

1. 5 day visit with Dr. Einaudi and Dr. Grivet at NASA-Goddard to learn the application of wavelet analysis to the FAO microbarograph network.
2. 1 day visit with Dr. Paul Neiman of NOAA to discuss NOAA profiler data.
3. Hoffman, E. G., L. F. Bosart, and D. Keyser: Large-Amplitude Inertia Gravity Wave environments: A Case Study. Seminar at the Illinois Water Survey, 20 August 1999, Champaign, Illinois.

VII. INVENTIONS AND PATENTS:

None.

VIII. FIGURES:

Fig 1.: Time series of meteorological variables at Flatland Atmospheric Observatory, near Champaign, Illinois, 28 April 1996: a) microbarograph pressure (hPa); b) wind speed (m s-1); and c) wind direction (deg.). The three vertical lines on the figure represent the beginning of the steep pressure fall, the pressure minimum and the end of the pressure rise. This figure illustrates the structure of the wave of depression as it passes Flatland. In a) a pressure drop of nearly 8 hPa in 30 minutes occurs between 1545 and 1615 UTC. This pressure drop is accompanied by strong and gusty easterly winds (b and c). As the pressure recovers the winds turn briefly northeasterly and speed decreases.

Fig 2.: Figure 2. Time-height section of the vertical velocity (m s^{-1}) from the Flatland 50 MHz Profiler, 1400-1800 UTC 28 April 1996. Dark (light) shading indicates upward (downward) vertical motion as indicated by the arrows. The three vertical lines correspond the lines on Fig. 1. This figure shows that the pressure fall is associated with a strong downward vertical motion in the middle troposphere (3000-6000 m AGL) and the pressure minimum in the wave of depression occurs immediately after this maximum in downward motion has ended.

1X. HONORS/AWARDS:

None during the grant period. However, the Co-PIs have been recognized for their significant research and professional service contributions by the American Meteorological Society (AMS) as follows:

Lance F. Bosart	Daniel Keyser
Elected AMS Fellow: 1983	Clarence L. Meisinger Award: 1989
Jule G. Charney Award: 1992	Editor's Award (AMS *Mon. Wea. Rev.*): 1989

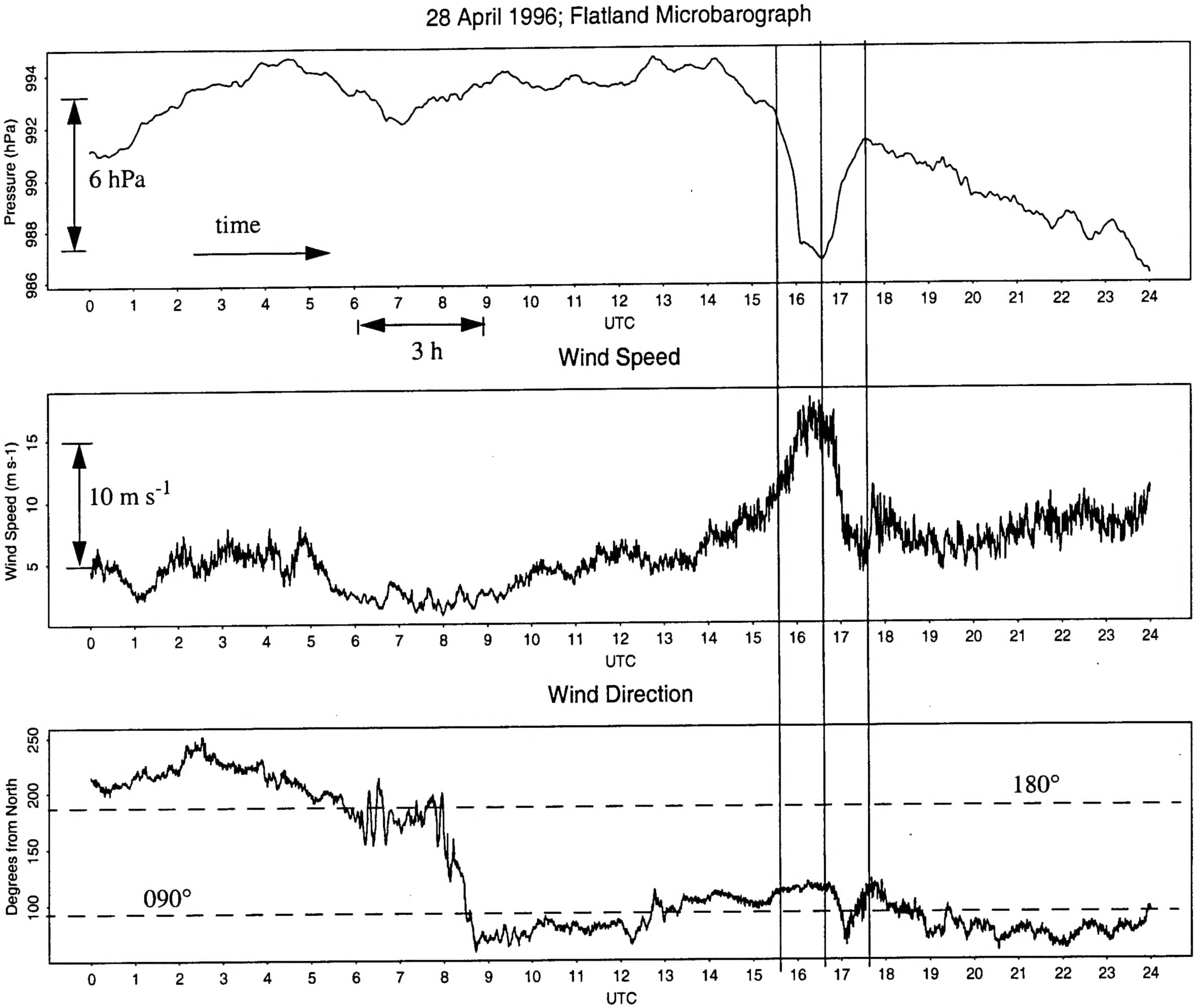


Figure 1. Time series of meteorological variables at Flatland Atmospheric Observatory, near Champaign, Illinois, 28 April 1996: a) microbarograph pressure (hPa); b) wind speed (m s^{-1}); and c) wind direction (deg).

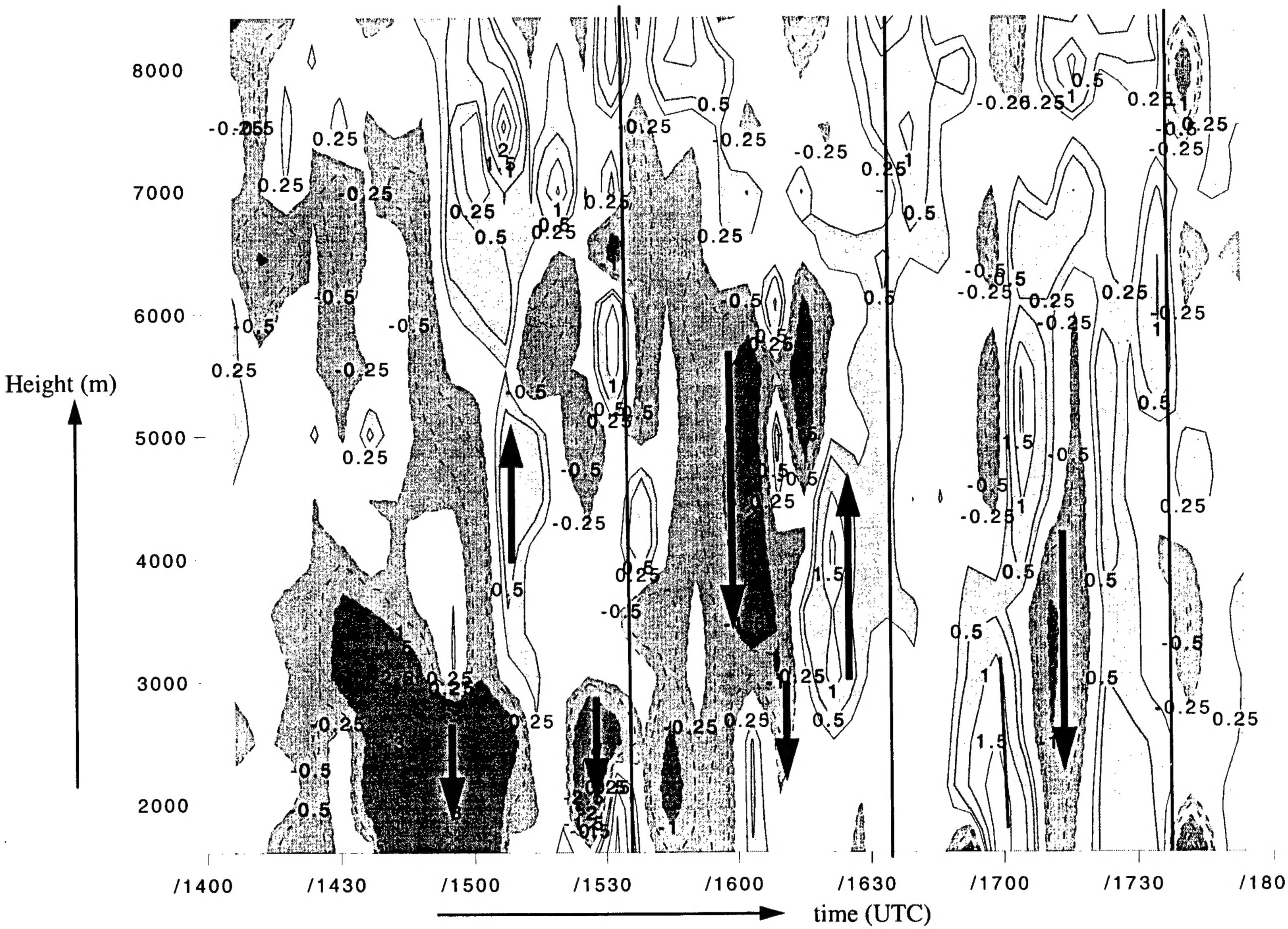


Figure 2. Time-height section of the vertical velocity (m s-1) from the Flatland 50 MHz Profiler, 1400 – 1800 UTC 28 April 1996. Dark (light) shading indicates upward (downward) verrtical motion as indicated by the arrows. The three vertical lines correspond the lines on Fig. 1.

1.1

LARGE-AMPLITUDE INERTIA-GRAVITY WAVE ENVIRONMENTS: LARGE-SCALE STRUCTURE AND EVOLUTION

Eric G. Hoffman*, Lance F. Bosart, and Daniel Keyser

University at Albany
State University of New York
Albany, New York

1. INTRODUCTION

In the last decade, atmospheric science researchers have begun to identify the environments associated with mesoscale gravity waves (MGWs). Qualitative similarities between MGW environments from a small sample (13) of published case studies have been noted by Uccellini and Koch (1987, hereafter UK87). UK87 showed that these waves tend to occur poleward of a surface frontal boundary situated beneath the inflection between an upper-level trough/ridge couplet. Additionally, UK87 observed an upper-level jet streak moving through the trough toward the downstream ridge. Other climatological investigations (e.g., Siedlarz and Koch 1996; Grivet-Talocia et al. 1999), consisting primarily of small-amplitude MGW events, have either not documented the wave environment or have only done so qualitatively. Koppel et al. (1999, hereafter K99) have recently compiled a climatology of large-amplitude inertia-gravity wave (IGW) events (defined on the basis of hourly surface pressure changes > 4.5 hPa). K99 distinguish IGWs from MGWs on the basis of possible inertial effects associated with longer lifetimes. K99 examined the composite IGW environment for a small number of cases and found quantitative results similar to those of UK87. However, no comprehensive quantitative investigations of the evolution of the *large-scale environments* associated with large-amplitude IGWs (hereafter IGW will refer to large-amplitude only) are known to exist.

Knowledge of the relationship between the evolving large-scale environment and the life cycle of IGWs is critical to an increased understanding of wave genesis mechanisms, an important unresolved scientific issue, and to forecasting the significant weather events often associated with wave passage. Here we will concentrate on identifying the characteristic three-dimensional structures and evolutions of large-scale environments conducive to the formation and presence of IGWs. The evolution of the three-dimensional composite of one of these IGW environments over the 48 h period prior to the wave events is presented in section 2, and a brief discussion of the results follows in section 3.

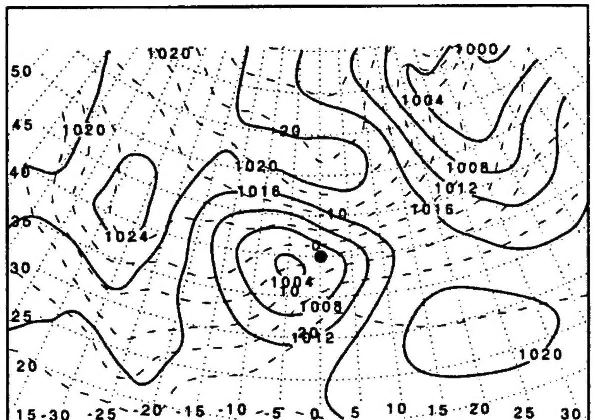
2. THREE-DIMENSIONAL COMPOSITES

2.1 Data and Methodology

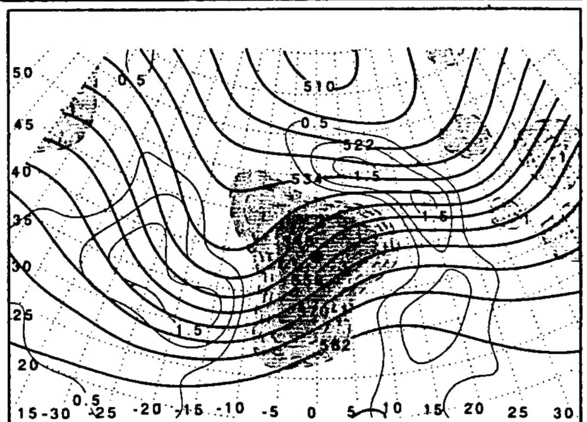
Three-dimensional composites are constructed using the National Centers for Environmental Prediction (NCEP) reanalyses archived at the National Center for Atmospheric Research (NCAR). These analyses have a 2.5° x 2.5° horizontal resolution and are interpolated to 50 hPa resolution in the vertical. A 100° x 50° degree grid (41 x 21) centered on distinct IGW events identified by K99 is extracted from the global analyses. These extracted grids are then composited for the winter (Nov. – Mar.) and spring (Apr. – Jun.) seasons in four regions of the United States (Midwest, Northeast, Southern Plains and Southeast) in order to examine seasonal and regional variability. This procedure is repeated from 48 h prior ($t_0 - 48$) through 12 h after ($t_0 + 12$) the time nearest to the IGW event (t_0) in order to study the evolution.

2.2 Results

The composite results for the Northeast (defined as the



1A. Northeast Winter SLP. (solid, hPa, Int=4)
Temperature (dash, C, interval=5) n=23



1B. Northeast Winter: 500hPa Hgt (dam, Int=6);
Vertical Velocity (x10-1 Pa s-1, shaded < 0.5)

Figure 1. Northeast winter composite. IGW observed at grid center (40°N, 0°W): a) Sea level pressure (hPa, solid) and 1000 hPa temperature (°C, dashed), with n indicating the number of IGW events in the composite; b) 500 hPa height (dam, thick solid) and vertical velocity (10^{-1} Pa s^{-1}, thin solid/dashed, shaded < -0.5).

* *Corresponding author address*: Eric G. Hoffman, ES-333, Dept. of Earth and Atmospheric Sciences, University at Albany, State University of New York, 1400 Washington Ave., Albany, NY 12222; e-mail: <eric@atmos.albany.edu>

region bounded by the Canadian border, 83°W, 36.5°N, and the Atlantic Ocean) winter at the time of the IGW event is shown in Fig. 1. In all figures, the center of the grid (40°N, 0°W) is marked with a black dot indicating the position of each IGW event. At the surface (Fig. 1a), the IGW is observed east and slightly north of the composite low center in a region of enhanced temperature gradient that extends eastward from the low, suggestive of the composite warm front. The flow at 500 hPa (Fig. 1b) features a relatively short wavelength trough/ridge couplet with the inflection between the trough and ridge over the IGW region. These upper-level features are also well represented at 250 hPa and on the dynamic tropopause (1.5 PVU surface, not shown). The vertical velocity at 500 hPa shows a broad region of upward motion downstream of the trough with a small area of maximum upward motion ($< -3.5 \times 10^{-1}$ Pa s^{-1}) concentrated over the IGW location.

The Northeast winter composite 500 hPa height and vertical velocity evolution over the two day period leading up to the IGW events is shown in Figure 2. The flow at $t_0 - 48$ h (Fig. 2a) is characterized by a long-wave trough located 2500 km to the west of the IGW region and a broad flat ridge over the IGW location. A two-sided Student's t test (not shown) reveals this trough to be statistically significant at the 99% level with respect to the weighted monthly climatology. There is a broad area of downward vertical motion upstream of the trough axis but only a small area of upward motion downstream. At the surface (not shown), a weak inverted trough is located downstream of the upper-level trough. At $t_0 -$ 24 (Fig. 2b), the trough amplifies and moves eastward while the ridge remains relatively stationary. A broad area of upward motion is now observed downstream of the trough axis. At the surface (not shown), the inverted trough moves eastward in conjunction with the upper-level trough but does not deepen appreciably. Finally, the next 24 h period (Fig. 1b) exhibits further amplification of the trough and steady movement toward the downstream ridge, leading to a significant decrease in the downstream half-wavelength and a concurrent amplification and contraction of the region of upward vertical motion. The inverted trough at the surface deepens, closes off, and also moves toward the IGW region (Fig. 1a).

3. DISCUSSION

We have quantitatively identified several three-dimensional environments associated with IGW life cycles, one of which is described here. These three-dimensional composite IGW environments are similar to those described qualitatively by UK87. The evolution of the large-scale features at 500 hPa shows that the troughs associated with IGWs can be identified at least two days in advance. Given this information, it may be possible for forecasters to identify features in the medium range (> 2 days) that have the potential to develop characteristics of IGW environments in the short range, such as a short wavelength trough/ridge couplet.

An essential feature of the evolution of the three-dimensional IGW environments is the amplification and scale contraction of the midtropospheric vertical motion pattern associated with the evolving trough/ridge couplet aloft. The dynamical significance of this scale contraction and its relationship to unbalanced flow associated with large divergence tendencies aloft is the subject of continuing research. Additional ongoing research involves several case studies utilizing Doppler radar and profiler data in order to quantify the structures and evolutions of IGW environments on the mesoscale.

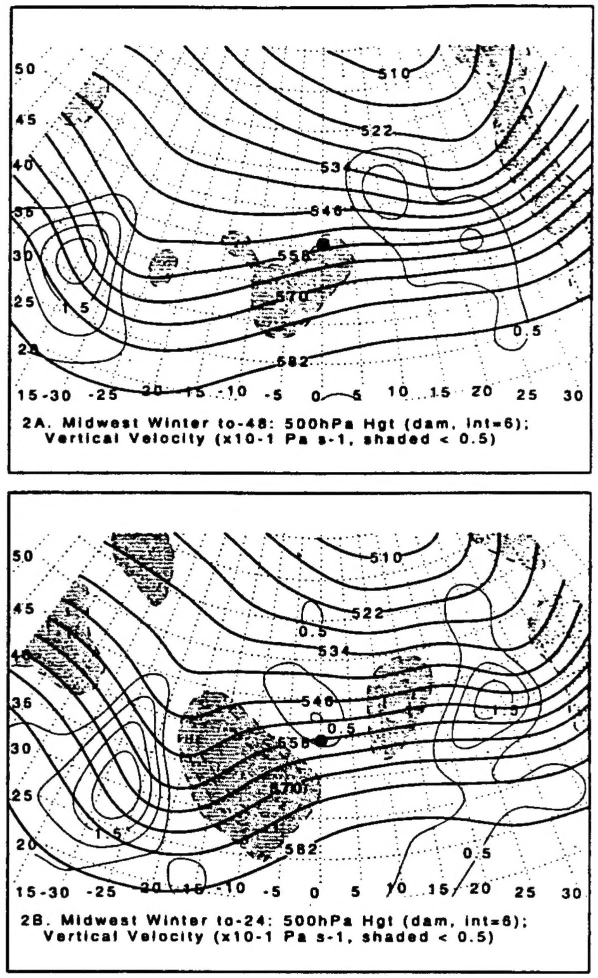


Figure 2. Northeast winter composite evolution. 500 hPa height (dam, solid) and 500 hPa vertical velocity (10^{-1} Pa s^{-1}, shaded < -0.5): a) 48 h prior to IGW occurrence ($t_0 - 48$), b) 24 h prior to IGW occurrence ($t_0 - 24$).

Acknowledgments. This research has been supported by the United States Air Force Office of Scientific Research through Grants F49620931O002 and F49620951O492 and by the National Aeronautics and Space Administration through Grant NAG57469.

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Koppel, L. L., L. F. Bosart, and D. Keyser, 1999: A 25-year climatology of large-amplitude hourly surface pressure changes over the conterminous United States. *Mon. Wea. Rev.*, **127**, in press.

Siedlarz, L. M., and S. E. Koch, 1996: A climatology of mesoscale wave disturbances seen in surface mesonet data during STORM-FEST. Preprints, *15th Conference on Weather Analysis and Forecasting*, Norfolk, VA, Amer. Meteor. Soc., 249–252.

Uccellini, L. W., and S. E. Koch, 1987: The synoptic setting and possible energy sources for mesoscale wave disturbances. *Mon. Wea. Rev.*, **115**, 721–729.

3.6 Mesoscale Structure and Evolution of Large-Amplitude Inertia-Gravity Waves: A Case Study

Eric G. Hoffman*, Lance F. Bosart, and Daniel Keyser

University at Albany
State University of New York
Albany, New York

1. Introduction

In the last decade, atmospheric researchers have begun to identify the environments associated with mesoscale gravity waves (GWs). Qualitative similarities between GW environments from a small sample (13) of published case studies have been noted by Uccellini and Koch (1987, hereafter UK87). UK87 showed that GWs tend to occur poleward of a surface frontal boundary situated beneath the inflection between an upper-level trough/ridge couplet. Additionally, UK87 observed an upper-level jet streak moving through the trough toward the downstream ridge. Other climatological investigations (e.g., Siedlarz and Koch 1996; Grivet-Talocia et al. 1999), consisting primarily of small-amplitude GW events, have either not addressed the GW environment or have only done so qualitatively. Koppel et al. (1999, hereafter K99) have recently compiled a climatology of large-amplitude inertia-gravity wave (IGW) events (defined on the basis of hourly surface pressure changes > 4.5 hPa). K99 distinguish IGWs from gravity waves (GWs) on the basis of possible inertial effects associated with longer life cycles. K99 examined the composite IGW environment for a small number of cases and found quantitative results similar to those of UK87. However, no comprehensive quantitative investigations of the *environments* associated with large-amplitude IGWs (hereafter IGW will refer to large-amplitude only) are known to exist.

Knowledge of the relationship between the evolving multiscale environment and the life cycle of IGWs is critical to an increased understanding of wave genesis mechanisms, an important unresolved scientific issue, and to short-term forecasting of the significant weather events often associated with wave passage. The goal of this research is to identify the characteristic three-dimensional structures and evolutions of environments conducive to the formation and presence of IGWs. A brief synopsis of our previous composite analyses of the IGW environment (Hoffman et al. 1998) is presented in section 2. Preliminary results of a case study of an IGW event on 28 April 1996 are presented in section 3 in order to draw comparisons with the composite results and to enable future documentation of the structure and evolution of the mesoscale IGW environment.

2. Synoptic Structure and Evolution

The three-dimensional structure and evolution of IGW environments is investigated using the National Centers for Environmental Prediction (NCEP) reanalyses archived at the National Center for Atmospheric Research (NCAR). Composite gridded analyses of IGW events identified by K99 are prepared for 48 h prior ($t_0 - 48$) through 12 h after ($t_0 + 12$) the time nearest to the IGW event (t_0) These analyses show (cf. Hoffman et al. 1998) that IGW environments are associated with an evolving upper-level flow in which a long-wave trough/ridge couplet amplifies and contracts, and an accompanying surface cyclone slowly deepens over two or more days. At $t_0 - 48$ h, the composite upper-level flow features a broad flat ridge over the incipient IGW region and a long-wave trough 1000 km to the west. Over the next 48 h, the trough amplifies and moves eastward while the ridge amplifies and remains nearly stationary, leading to a scale contraction in the downstream half wavelength. In addition, a surface cyclone downstream of the trough also moves eastward and slowly deepens. This evolution leads to an IGW environment at time t_0 characterized by: 1) a low-level stable layer northeast of a surface cyclone, 2) a short-wavelength trough/ ridge couplet aloft with its inflection point directly over the IGW region, 3) a jet maximum in the southwesterly flow on

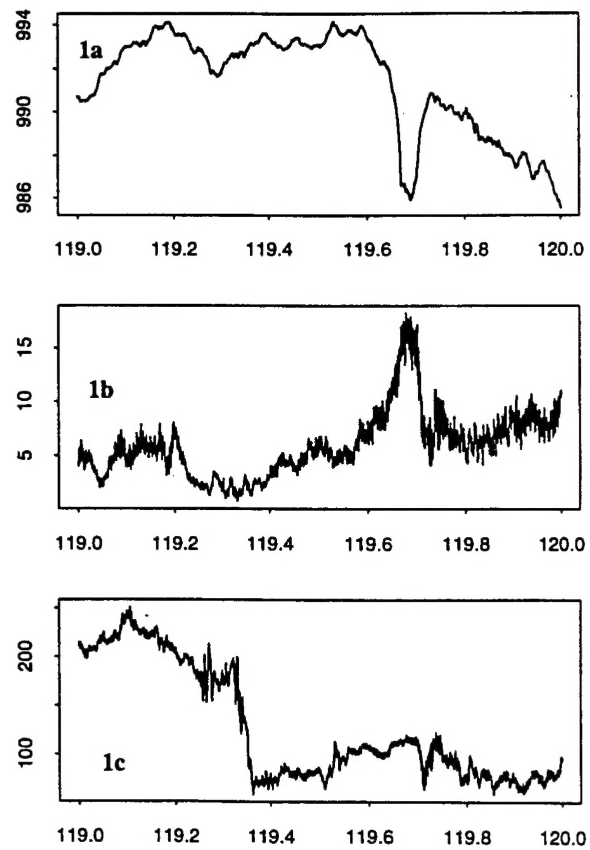

Figure 1. Time series at Flatland Observatory, IL, from 0000 UTC 28 – 0000 UTC 29 April 1996 (Julian Day 119): a) pressure (hPa); b) wind speed (m s^{-1}); and c) wind direction (deg).

* *Corresponding Author address*: Eric G. Hoffman, ES-333, Dept. of Earth and Atmospheric Sciences, University at Albany, State University of New York, 1400 Washington Ave., Albany, NY 12222; e-mail: <eric@atmos.albany.edu>

the downstream side of the trough, and 4) a second jet maximum downstream and poleward of the IGW region in an area of large-scale confluence.

3. Case Study - 28 April 1996

During the morning hours of 28 April 1996, an IGW develops over Kansas in association with a mesoscale convective system. Data from the surface, the National Weather Service profilers and WSR-88D radars show that the IGW translates northeastward, ahead of the convection, across Missouri and into Illinois in the low-level stable layer northward of a warm front. The IGW passes through the Flatland Atmospheric Observatory's (FAO) microbarograph network near Urbana-Champaign, IL, at about 1900 UTC. The microbarograph trace from Flatland (Fig. 1a) shows a wave of depression with pressure falls of ~8 hPa in 30 minutes. The meteorological observations from Flatland show that the wave is accompanied by gusty easterly winds (Figs. 1b and 1c). Wavelet analysis of the FAO network (Grivet-Talocia and Einaudi 1998) is used to identify the following wave characteristics: 1) a peak-to-peak amplitude of 6.04 hPa, 2) a period of 4.4 h, and 3) a phase speed of ~21 m s^{-1} toward the east-southeast. These observations are consistent with other case studies (e.g., Koch and Golus 1988; Schneider 1990; Bosart et al. 1998). In addition, the vertical velocities from a 50 MHz profiler at FAO indicate the presence of the wave throughout the lower troposphere (not shown).

The three-dimensional environment in which this IGW forms is investigated using the NCEP global analyses. Many, but not all, of the characteristics described in section 2 are found for this case. The IGW forms and translates in the low-level stable layer northeast of a surface cyclone and northward of a warm front (Fig. 2a). The upper-level flow features a trough over the eastern Rockies with a broad ridge over the central United States (Fig. 2b), rather than the short-wavelength trough/ridge couplet observed in the composite. Only one significant jet maximum at 250 hPa is located north and east of the IGW region over the Great Lakes (Fig. 2b). A jet maximum is noticeably absent on the downstream side of the trough. The 500 hPa vertical velocity field (not shown) shows a distinct mesoscale maximum over western Illinois. A similar maximum is also observed in the composites (Hoffman et al. 1998). The evolution of the upper-level flow (not shown) is similar to composite evolution. A long-wave trough slowly deepens and approaches a nearly stationary downstream ridge, thereby amplifying the trough/ridge couplet.

In conclusion, many of the features in the composite study can be found in this individual case. Future work will investigate the mesoscale environment in which the wave exists and the structure of the wave itself through use of the WSR-88D radars, the Profiler network and wavelet analysis of the 50 MHz profiler data at FAO.

Acknowledgments. This research has been supported by the United States Air Force Office of Scientific Research through Grants F4962093100002 and F49620951 0492 and by the National Aeronautics and Space Administration through Grant NAG57469. Thanks to Dr. Franco Einaudi and Dr. Wallace Clark for providing access to the FAO microbarograph, profiler and meteorological data, and to Dr. Stefano Grivet for use of his wavelet analysis algorithms.

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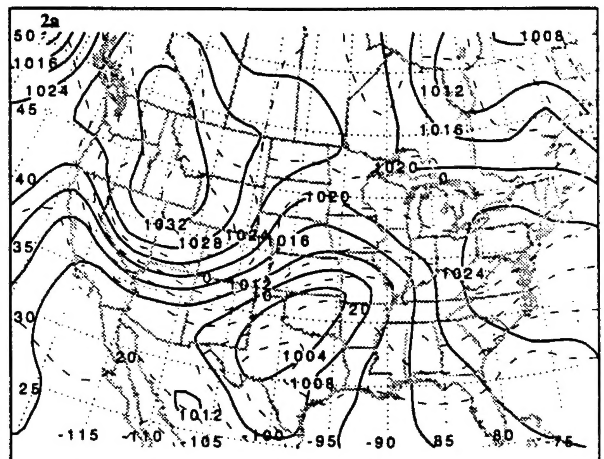
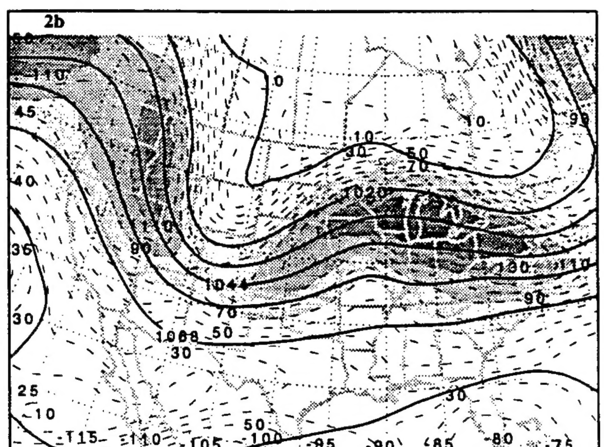


12 UTC 28 Apr 1996, MSL Pres. (solid, hPa, int=4)
Temperature (dash, C, interval=5)



12 UTC 28 Apr 1996: 250hPa Hgt (solid, dam, int=12),
isotachs (dashed, kts, int=10, shaded > 70)

Figure 2. 1200 UTC 28 April 1996: a) sea level pressure (hPa, solid) and surface temperature (°C, dashed); b) 250 hPa height (dam, solid) and wind speed (kts, dashed, shaded > 70).

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Lance F. Bosart
518-442-4564

A 25-yr Climatology of Large-Amplitude Hourly Surface Pressure Changes over the Conterminous United States

LORNA L. KOPPEL, LANCE F. BOSART, AND DANIEL KEYSER

Department of Earth and Atmospheric Sciences, The University at Albany, State University of New York, Albany, New York

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ABSTRACT

Hourly surface pressure observations for a 25-yr period (1949–63; 1984–93) for the conterminous United States have been used to map the distribution of large hourly pressure changes defined as falls or rises in excess of 4.25 hPa. Initially, 8431 reports satisfying this pressure change threshold were obtained. After error checking, this number was reduced to 5380 occurrences. Large hourly surface pressure changes are most common over the Great Plains and New England and least common over the Southeast and Southwest. Large pressure falls are confined almost exclusively to the Plains, upper Midwest, and New England, and are virtually absent over the Intermountain West and parts of the Appalachians.

A manual (subjective) analysis identified 1038 inertia–gravity wave (IGW) occurrences from the 5380 large hourly surface pressure change occurrences. IGW occurrences are most common across the Plains and from the Great Lakes toward western New England, and are virtually absent across the Intermountain West. A partitioning of IGW occurrences on the basis of weather type reveals that IGWs associated with cyclones occur preferentially from Nebraska eastward across the Great Lakes to New England, while IGWs associated with convection are mostly confined to the Plains.

IGW occurrences are most likely seasonally in winter and spring and diurnally near 0300 and 1200–1300 LST. Considerable interannual variability is seen in the distribution of 579 IGW events (an event may include IGW occurrences at several stations). Twenty-three IGW events (roughly 2 events per month) occur each year over the conterminous United States and 8 of the 23 events involve multiple stations. IGW events are most prevalent during the March–June period.

Representative composites of mean sea level pressure, 1000–500-hPa thickness, 500-hPa geopotential height, and 500-hPa geostrophic wind are shown for cool season (November–April) IGW events associated with cyclones and early warm season (May–June) IGW events associated with convection. The composites show that IGWs occur preferentially in a warm air advection region to the northeast of the surface cyclone center poleward of a frontal zone and beneath a band of relatively strong southwesterly flow at 500 hPa. The composite results are in broad agreement with the signatures identified by Uccellini and Koch as generally common to occurrences of large-amplitude IGW events identified in the literature.

1. Introduction

Numerous investigators have documented the existence of long-lived, mesoscale gravity waves (some of which are large amplitude) during the last five decades (see, e.g., Brunk 1949; Tepper 1954; Ferguson 1967; Bosart and Cussen 1973; Young and Richards 1973; Uccellini 1975; Miller and Sanders 1980; Stobie et al. 1983; Bosart and Sanders 1986; Zack and Kaplan 1987; Bosart and Seimon 1988; Branick et al. 1988; Koch and Golus 1988; Schneider 1990; Bauck 1992; Ralph et al. 1993; Ramamurthy et al. 1993; Bracken 1995; Koch and O'Handley 1997; Bosart et al. 1998). These mesoscale gravity waves typically have amplitudes of 2–6 hPa, wavelengths of 150–300 km, periods of 2–3 h, and phase speeds of 15–35 m s^{-1}. They tend to be found in a large-scale environment containing a wave duct (defined as a prominent stable layer in the lower troposphere) that is situated beneath a deep quasi-neutral layer containing a critical level (where the observed wave phase speed matches the observed wind speed in the direction of wave propagation). This environmental structure has been shown by Lindzen and Tung (1976) to be favorable for wave overreflection, amplification, and maintenance. As discussed in many of the above-referenced papers, the passage of prominent mesoscale gravity waves can be associated with significant and disruptive weather changes. Although the vertical structure of prominent mesoscale gravity waves has not been documented as extensively as their horizontal structure, observational evidence has been accumulating that suggests they can span the troposphere (see, e.g., Pecnick

Corresponding author address: Prof. Lance F. Bosart, Department of Earth and Atmospheric Sciences, The University at Albany, State University of New York, 1400 Washington Ave., Albany, NY 12222.
E-mail: bosart@atmos.albany.edu

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